Science Highlights and Lessons Learned from the Atmospheric Infrared Sounder (AIRS)

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ABSTRACT

The Atmospheric Infrared Sounder (AIRS) and companion instrument, the Advanced Microwave Sounding Unit (AMSU) on the NASA Earth Observing System Aqua spacecraft are facility instruments designed to support measurements of atmospheric temperature, water vapor and a wide range of atmospheric constituents in support of weather forecasting and scientific research in climate and atmospheric chemistry. This paper is an update to the science highlights from a paper by the authors released last year and also looks back at the lessons learned and future needs of the scientific community. These lessons not only include requirements on the measurements, but scientific shortfalls as well. Results from the NASA Science Community Workshop in IR and MW Sounders relating to AIRS and AMSU requirements and concerns are covered and reflect much of what has been learned and what is needed for future atmospheric sounding from Low Earth Orbit.

Keywords: NASA, Satellite, Atmosphere, Weather, Climate, Atmospheric Composition

1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) on the Aqua spacecraft measures the hyperspectral infrared spectrum of the atmosphere from 3.7-15.4 microns with nearly twice global daily coverage (Chahine, 2006). The Advanced Microwave Sounding Unit (AMSU) is a microwave radiometer with 15 channels ranging from 23.8 GHz to 89 GHz. National Weather Prediction (NWP) centers worldwide assimilate the AIRS and AMSU data with these instruments providing the highest forecast improvement of any other sensors. The spectra are also used to retrieve cloud cleared radiances and atmospheric temperature and water vapor profiles with high accuracy and product resolutions approaching 50km per retrieval. Assimilation of these products into the forecast models has shown considerably higher impact than radiances alone, however, this methodology has not yet become operational at the NWP centers. Additional products including cloud properties and trace gases including carbon monoxide, methane, carbon dioxide, and sulfur dioxide are also retrieved from AIRS and used in a wide variety of scientific investigations. These investigations include atmospheric transport and global circulation, atmospheric chemistry, climate processes and anthropogenic impacts to Earth's atmosphere. A description of the AIRS data products and a comprehensive survey of science accomplishments covering the period from launch to 2010 is given in a prior writing (Pagano et al., 2010a).

2. RECENT SCIENCE HIGHLIGHTS

The science discovery continues with the AIRS/AMSU measurement system (heretofore referred to as AIRS) with significant discoveries in the areas of weather forecast improvement, climate variability and change, and atmospheric composition. Figure 1 shows the total number of peer reviewed publications since 2002. We discuss below science highlights using AIRS data in these science disciplines that can be found in the peer reviewed literature that have occurred since the prior survey performed in 2010 (Pagano et al., 2010a).

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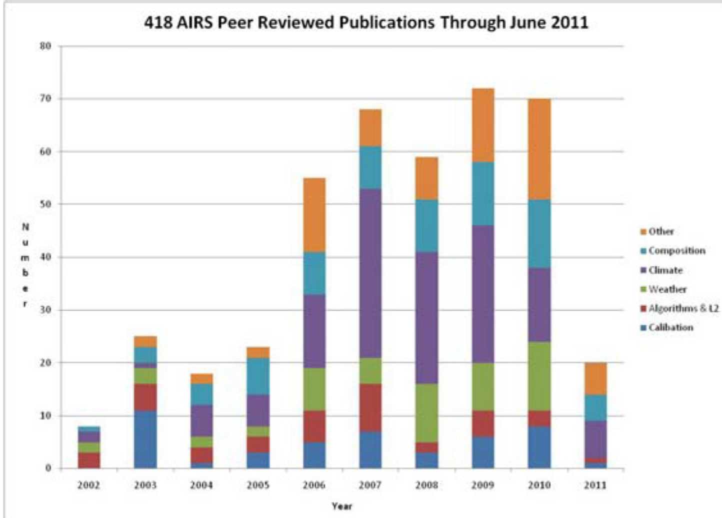

Figure 1. Count of peer reviewed science publications by discipline using AIRS data since launch through June 2011.

2.1 Weather Forecast Improvement

While the National Center for Environmental Protection (NCEP) assimilates AIRS radiances operationally and has shown considerable positive impact, progress in this area has limited by the difficulty assimilating radiances under cloudy conditions. Research continues on assimilating the retrieved cloud-cleared temperature profiles which have significantly higher yield than clear radiances with valid retrievals up to 70–80% cloud fraction. Researchers at the Shanghai Typhoon Institute in conjunction with several US Universities used a newly developed highly efficient 4D data assimilation scheme called the Local Ensemble Transform Kalman Filter (LETKF) and a reduced resolution version of the NCEP model to evaluate the impact of assimilating AIRS data on forecast accuracy. Results showed significant and consistent positive impact in the Southern Hemisphere and positive but less significant improvement in the Northern Hemisphere (Li, 2011). Typically the Northern Hemisphere forecast accuracy is considerably better than the Southern Hemisphere due to the abundance of radiosonde observations over land.

The Saharan air layer (SAL) is a dry, warm layer of air in the lower troposphere over the Atlantic Ocean extending westward of the African coast to the Caribbean Sea. Prior studies have demonstrated that the SAL can lead to thermal gradients in the atmosphere that contribute to the formation of tropical cyclones. Other studies have shown that the SAL can suppress tropical cyclones when this air intrudes into the inner regions of the newly forming cyclone. In a recent study performed by researchers at Nanjing University and NASA GSFC, AIRS data were incorporated in to the MM5 model using a "nudging technique" to demonstrate that, in fact, both phenomenon occurred influencing the formation of Hurricane Isabel and TD14 (Pan et al., 2011).

2.2 Climate Variability and Change

AIRS observes a wide variety of atmospheric processes, as reported in several recent publications about climate processes. Air-sea interactions were examined by Shimada and Minobe (2011), who demonstrated that surface wind divergence driven by sea surface temperature gradients has an effect on the atmospheric structure observed by AIRS. In another study of atmosphere-ocean interactions, Kruger and Grabl (2011) used AIRS lower tropospheric geopotential heights to define the Antarctic Polar Front, and correlated frontal locations with cloud condensation nuclei produced by diatoms at the frontal boundary. AIRS data are also being used to estimate fluxes of heat and moisture between the atmosphere and underlying land (Ferguson and Wood 2010) or ocean (Dong et al. 2010). Despite the challenges of heat flux estimation, the AIRS observations give more realistic results than do model simulation. The thermal structure of the atmospheric boundary layer in subtropical and polar regions was described by Martins et al. (2011) and Pavelsky et al. (2010), respectively. Both these studies compared AIRS with model reanalyses, and concluded the AIRS observed more realistic boundary layer structure. Guan et al. (2010) looked at "atmospheric rivers" over the West Coast of the United States; these events are a significant source of precipitation in this region. They demonstrated that AIRS near-surface temperatures are more highly correlated with snowfall than are NCEP model surface temperatures. This suggests that AIRS observations can be used to improve forecasts of high-snowfall conditions.

Clouds and deep convections are a common topic of AIRS-based research. Montoux et al. (2010) used numerical model fields and AIRS water vapor observations to study the conditions for cirrus cloud formation over France. They noted the value of the water vapor observations in simulating realistic cloud fields. In a more global study, Liang et al. (2011) created a water vapor and temperature record reaching from the surface to the middle atmosphere by combining observations from AIRS and from the Microwave Limb Sounder instrument, also flying in the A-Train satellite constellation. Upper tropospheric water vapor was the subject of a study by W. Tian et al. (2011), who examined vertical transport processes, including stratosphere-troposphere exchange, over the Tibetan Plateau. Vertical transport was also the subject of a study by Russo et al. (2011). They used AIRS and other observational data sources to examine vertical transport in several numerical weather prediction models. The most obvious effect of deep convection –deep clouds— were described in a study by Aumann et al. (2011). They were able to identify several thousand deep clouds in the AIRS radiances, and correlate them with such signatures as a lifted tropopause.

Garand et al. (2011) critiqued the commonly used CO2 slicing technique for estimating cloud properties by comparing AIRS observations and model simulations. They concluded that consistent definitions are needed for proper comparisons of derived cloud quantities. Cloud properties from AIRS and the MODerate-resolution Imaging Spectroradiometer (MODIS) were compared by Nasiri et al. (2011). They showed that derived cloud properties from the two instruments are radiatively consistent despite large differences in spectral and spatial resolution.

2.3 Atmospheric Composition

Carbon monoxide is an air pollutant that is produced by incomplete burning as is the case with forest fires. It contributes to the global carbon cycle, eventually turning into CO_2, but is not a major contributor to total greenhouse gas feedback. Scientists from the Japanese National Institute of Environmental Studies measured increases in CO using shipboard instruments resulting from emissions in Southeast Asia and Northern Australia (Nara et al., 2011). While the shipboard measurements determined the concentration of CO, the AIRS data were useful in identifying where the CO originated. The CO/CO_2 ratios indicated that the majority of the CO was from burning peat soil in Indonesia.

Global Circulation Models (GCMs) are useful for understanding transport of weather patterns and trace gases within the atmosphere. For many years, the absence of accurate CO_2 data have made validation of transport of this gas within these models limited to aircraft in-situ measurements and ground station measurements. AIRS provides over 15,000 retrievals of CO_2 in the mid-troposphere distributed randomly across the globe, usually in regions of low cloudiness. A typical monthly map of CO_2 data from AIRS obtained by averaging the month of June from 2003–2010 is shown in Figure 2. In a recent study led by researchers at the University of Edinburgh, CO_2 concentrations calculated by the NASA GEOS-Chem GCM were compared to several data sets including the AIRS mid-tropospheric CO_2 over the period of 2004–2006 (Feng et al., 2011). AIRS data compare well with the GEOS-Chem model with small biases observed in the mid-tropospheric CO_2 trends.

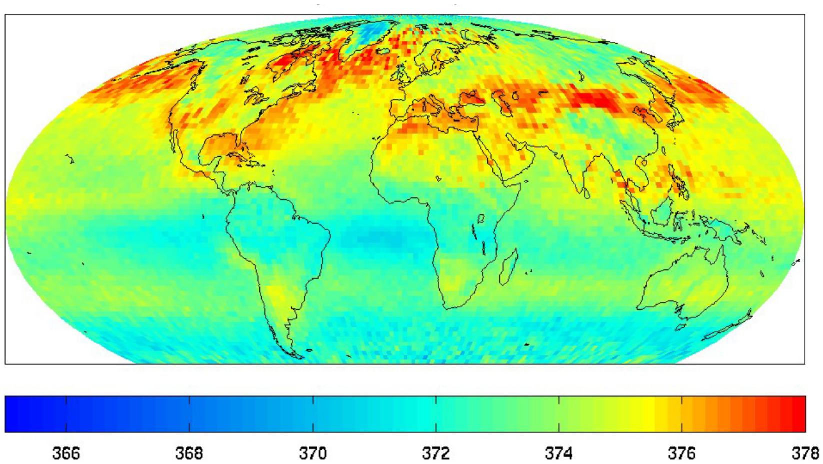

Figure 2. AIRS Mid-tropospheric CO_2 for a typical June as produced by averaging the L3 product for all months of June between 2003 and 2010 (Pagano et al., 2011).

One of the problems with measurements of CO_2 is they are highly sensitive to cloud cover resulting in very low yield. As mentioned above, AIRS achieves 15,000 CO_2 retrievals per day compared to over 3 million raw measurements made by AIRS (Pagano et al., 2010b). Using a spatio-temporal mixed-effects model, optimal smoothing is performed to the AIRS CO_2 data to create continuous coverage globally on a daily basis (Katzfuss et al., 2011). Maps are accompanied by prediction uncertainties, and capture key features in the global transport of CO_2.

The AIRS mid-tropospheric CO_2 product has been used to study the Madden-Julian Oscillation (MJO) (Li et al., 2010; Tian et al., 2010) and La-Niña/El Niño (ENSO) (Jiang et al. 2010), and as such provides a unique constraint as well as a robustness test for coupled carbon-climate models. Bai et al. (2010) compared the AIRS product to ground-based and aircraft measurements, with a focus on China, concluding that the AIRS product is consistent with both sets of in situ measurements and is able to capture the seasonal variations.

Scientists have long known that temperature inversions trap air pollution, and cause unsafe conditions for residents in these areas. In one study, researchers found that sputum cell counts of neutrophilis, eosinophils macrophages and lymphocytes were increased in patients during times of temperature inversions (Wallace et al., 2011). AIRS data were used to identify the temperature inversions for this study in the city of Hamilton Ontario, Canada. Figure 3 shows a map of temperature inversions in this area. The AIRS Project is developing a temperature inversion alert indicator as a result of this research.

<to come>

Figure 3. TBD. Temperature inversions in the area of Hamilton, Ontario, Canada are an indicator of possible poor air quality.

3. SCIENCE LESSONS LEARNED

Capturing the lessons learned by the scientific community is a difficult task; fortunately, last year a sounding community workshop was held that we can draw upon. The NASA Science Community Workshop on Polar Orbiting IR and MW Sounders was held at the Greenbelt Marriott on November 1st and 2nd, 2010 (Figure 4) with a major objective to identify paths for data continuity and identify needs for further improvement (Fetzer edit., 2011). The workshop covered three theme areas of atmospheric sounding including breakout groups for Weather Forecast Improvement, Climate Prediction, and Atmospheric Composition. The report recommendations capture the lessons learned and future needs of the community and are presented below in summary form.

Figure 4. NASA Science Community workshop on Polar Orbiting IR and MW Sounders was held at the Greenbelt Marriott on November 1st and 2nd, 2010.

The workshop addressed the four key questions below. Question 1 relates to the value of the sounders. In addition to the recommendations below, a good discussion on the value of the sounders is given in the workshop report, and we have discussed the value of AIRS to weather, climate and atmospheric composition, both above and in prior writings. The other questions relate to NPP, future missions and the relation of sounders with the NRC Decadal Survey. We have extracted the recommendations from the workshop relating to each question and placed them below the corresponding question. In cases where questions 1–4 do not have a corresponding recommendation we add text in italics from the workshop report for the corresponding discipline relating to that question. Phrases in brackets are the authors' edits for clarification.

Q1. What is the range of scientific research currently carried out with atmospheric sounding instruments including AIRS, IASI-A, AMSU, TES, and MOPITT?

a. **Climate:** The value of monitoring long-term variability and extreme climate events should be emphasized in all sounding systems. Further research to generate new and improved products from AIRS and IASI is needed, especially with regard to cloud and dust microphysical and radiative properties. Other important cloud properties that are needed include cloud top temperature, phase, and optical properties. Improved theoretical techniques are needed for multiple scattering at finer spatial resolution. Fully characterize IASI performance with increasing cloud cover.

b. **Atmospheric Composition:** *There is a broad suite of research areas enabled by atmospheric sounders covering the carbon, nitrogen, and hydrological cycles, their coupling through atmospheric dynamics, atmospheric chemistry and application areas including surface fluxes of CO, CO_2, and natural hazards. In global atmospheric chemistry/air quality, these sounders have been used for chemical data assimilation, long-range transport of pollution (ozone and CO), estimation of CO sources and sinks, retrieval of ammonia and SO_2.*

c. **Weather:** NWP center(s) should undertake an objective evaluation of the use of cloud cleared radiances, specifically, in regions where profiles have shown large impact. Product developers should provide averaging kernels and/or error co-variance matrices in addition to quality control for all retrieval products. Add SSMIS to list of instruments covered in these questions.

Q2. How can the planned CrIS, ATMS, IASI-B, IASI-C continue to support the scientific research enabled by the EOS sounders?

a. **Climate:** [Fully characterize] the CrIS and IASI-B retrievals when these data sets become available. Develop retrieval algorithms for water isotopes (in addition to water vapor) because isotope observations are needed to constrain faster hydrologic processes.

b. **Atmospheric Composition:** The full spectral resolution possible from CrIS [should] be achieved for NPP and future flight units. An assessment [should] be made of the total composition products and retrieval accuracy of CrIS compared to the other IR sounders currently in orbit.

c. **Weather:** The sounding community should encourage multi-sensor characterization and inter-comparisons for long-term sensor validation. The spectral resolution of the CrIS short-wave and mid-wave bands should be increased to the full optical capability of 0.625 cm^{-1}. The CrIS SDR team should adopt the calibration approach that ensures the "best" performance even if the current approach meets specification. Specifically, this applies to inter-calibration of FOVs and non-linearity corrections. Add MIS to list of instruments in this question.

Q3. What requirements are needed from future sounders (e.g., post-EPS, post-NPOESS) to address the critical challenges in weather, climate, air quality, and carbon cycle research?

a. **Climate:** High vertical resolution, especially in the boundary layer, is needed to constrain fluxes in next-generation climate models. CO_2 (and other gases) for assimilation, along with temperature and humidity, are needed. Higher spectral resolution … will improve vertical resolution of sounding of trace gases. Future sounders should be designed with spectral resolution and coverage to obtain lower tropospheric HDO, as with TES. Increased horizontal resolution results in greater cloud contrast within the field of regard, and allows for successful soundings under more cloud conditions than achievable with AIRS. A higher spatial resolution (1 km) AIRS-like instrument should lead to improved land and ocean surface skin temperature, spectral emissivities, surface-leaving radiance fluxes, and cloud radiative properties. … Good radiometry is needed to retrieve cloud properties. Monitoring climate trends or small interannual changes require high stability. Collocated visible and IR observations are complementary for cloud characterization. Collocated microwave observations are needed to characterize state variables in the presence of clouds. GPS is needed to complement sounding.

b. **Atmospheric Composition:** Multi-spectral approaches should be considered, either through co-boresighting different instruments or extending the spectral range of IR sounders, to obtain near surface trace gas information.

c. **Weather:** *Hurricane forecasting requires very high spatial and temporal sampling at specific* times *and places (e.g., following hurricane formation and tracking). Low latency is important for global and mesoscale forecasting. Future hyperspectral instruments should be spatially and spectrally Nyquist sampled. Having full spectral coverage (similar to IASI) was considered valuable. Need rapid response to warnings such as* SO_2*/Volcanic ash, flooding, etc. One instrument may not meet all the requirements. Maintaining a stable orbit. Having the same sensor in multiple orbits with similar spatial sampling is desired. More sampling is needed in the tropics. ...* There is a need for a detailed OSSE to study optimal design trade-off between spatial resolution, spectral resolution, instrument noise, and temporal sampling.

Q4. How can planned and future sounders complement, or act as a bridge to NASA Decadal Survey missions?

a. **Climate:** An AIRS-class instrument, preferably at higher spatial resolution than AIRS, is highly complementary to CLARREO in resolving and explaining fine-scale structure in regional climate processes and variability. Two or more orbits at fixed local time are needed to describe the regional diurnal cycle. Improved boundary layer water vapor will lead to improved CO_2 retrievals from OCO and ASCENDS. Multiple instruments per platform allow multi-sensor cross calibration.

b. **Atmospheric Composition:** *The NASA Decadal Survey missions are predicated upon a strong polar observing system that includes the IASI and JPSS sounders [National Research Council, 2007]. These IR sounders will be the only means of continuing composition products initiated by TES, AIRS, and MOPITT. The primary composition platform, Aura, will not see a follow-on until the Global Atmospheric Chemistry*

Mission (GACM), which is slated to launch around 2030. As a consequence, these sounders will be the only bridge linking Aura trace gas observations to GACM observations. On the other hand, regional measurements of pollutants over North America will be provided by Geostationary Coastal and Air Pollution Events (GEO CAPE). However, these geo-stationary observations will need global trace gas observation from JPSS and IASI as boundary conditions. Aerosols and trace gas pollutants have in many cases the same sources. The future sounders of atmospheric composition could compliment the ACE aerosol measurements to provide additional constraints on aerosol precursors, e.g., ammonia, and sources. For greenhouse gases, sounder's broad spatial coverage and ancillary tracers, e.g., CO, can complement the ASCENDS mission, which will provide high resolution, narrow swath measurements of CO_2.

c. **Weather:** *[Much discussion is contained within the report on synergy with missions: GPS, PATH, GPM, ASCENDS, GOSAT, OCO, CLARREO] There is also concern that the JPSS mission is not sufficient to meet the evolving needs of the sounding community (as discussed in the text and recommendations above). The NPOESS IORD-II document (Pace et al. 2002) was written before the launch of Aqua, Aura, and METOP and does not incorporate many of these new areas of research into the requirements. Given funding realities, it is unlikely that these will become requirements within the JPSS program either. The DS did not appear to focus on these aspects in their analysis.*

One final recommendation was provided that did not fall under the categories above: "The sounding science community should hold annual meetings to strengthen prioritize and revise the recommendations from this workshop."

4. SUMMARY AND CONCLUSIONS

It has been a good start for 2011 science findings using AIRS data with over 20 peer reviewed papers published as of June in the areas of weather forecast improvement, climate prediction, and atmospheric composition. Scientists continue to work on methods for assimilating AIRS data, and studies of atmospheric processes, clouds and water vapor for understanding climate processes and model improvement comprise the bulk of the papers published using AIRS data. The use of AIRS carbon monoxide and carbon dioxide products continue to find importance to understanding global circulation patterns and long-range transport of these gases. The NASA Science Community Workshop on Polar Orbiting IR and MW Sounders held at the Greenbelt Marriott on November 1st and 2nd, 2010 identified numerous uses for sounding data that cannot be captured here, but is worth reading. Looking towards the future, the workshop identified several recommendations to address improved utilization of the sounders, future observational needs, and the synergy of the sounders with the NRC Decadal Survey for Earth Science at NASA. The AIRS/AMSU observing system and the science achieved with these instruments have improved our understanding of the Earth's atmosphere for improved weather forecasting, improved climate prediction and a better understanding of the transport of water vapor and greenhouse gases on a global scale.

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